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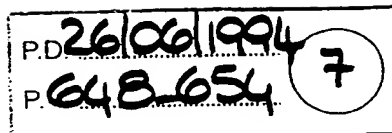
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## EVALUATION OF ADVANCED REGULATORS FOR AN EVAPORATION STATION

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### ABSTRACT

This paper presents the design and evaluation of three regulators for an industrial evaporation station: a conventional PI Controller, a Fuzzy Logic Controller and a Generalized Predictive Controller (GPC). Linearized models are derived to design the predictive controller. The process diagram, the instrumentation, the nonlinear model, the controllers design and the implementation are described. Performance of the three regulators are compared by simulation.

### 1. INTRODUCTION

One of the main stages in the sugar production, takes place in the evaporation station, where the sugar content of a juice rich in saccharose is increased by boiling. The resulting syrup is used to obtain sugar crystals in a set of vacuum pans. For the study we consider a specific beet sugar factory placed in Valladolid (Spain), which evaporation section is composed of five evaporators working as a four-effect system.

One of the most important aim of the control system of an evaporation station is to maintain the sugar concentration at the output of the station at prescribed values despite the disturbance effects. It is also very important to keep the level of juice in each evaporator between two security limits.

The complexity of the system dynamic and the presence of disturbances justify the use of advanced controllers.

The paper describes first the plant and the instrumentation. A derivation of a nonlinear model

of the station follows. Next, the plant is analyzed by simulation. The design of two regulators, based on fuzzy logic and generalized predictive control is then presented. The performance of both regulators is compared by simulation of the nonlinear dynamical model with the performance of a conventional PI controller. Conclusions are presented in the last section.

### 2. PLANT DESCRIPTION

Fig. 1 shows a two chambers evaporator. The heating chamber surrounds a set of vertical tubes that contain boiling juice. A flow of steam enters to this chamber and transfers heat to the juice providing the energy needed for boiling.

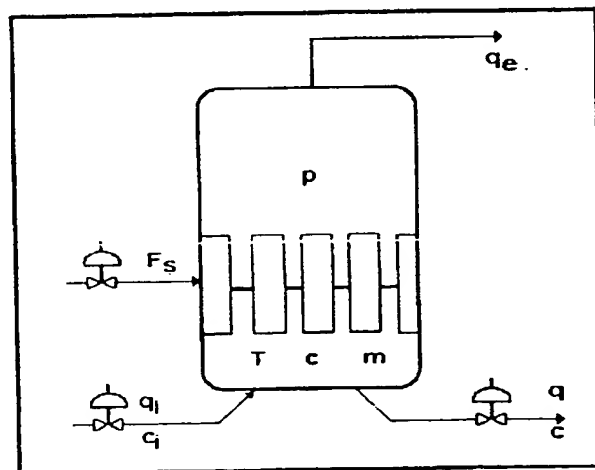


Fig. 1: A two chambers evaporator

The steam condenses around the tubes and leaves the evaporator as condensate. The

interior of the tubes, plus the evaporator upper and bottom spaces, form the juice chamber. A sugar solution of low concentration (juice) flows continuously into the base of the evaporator and starts boiling. Consequently, a solution of higher concentration is obtained at the output. The steam produced from the water evaporation reaches the upper space and leaves the juice chamber by a pipe at the top.

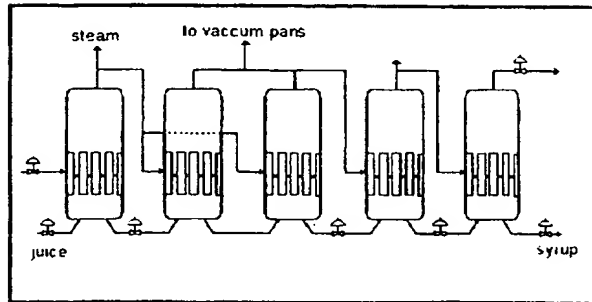


Fig. 2: Process diagram

Fig. 2 shows the process diagram. It consists of a set of five evaporators interconnected through pipelines and valves. The steam generated in one evaporator is used to provide energy to the next heating chamber, while the juice flows from one evaporator to another increases the sugar concentration. In this multiple-effect arrangement only the first evaporator is fed with fresh steam and juice. In the last evaporator, the evaporated steam scurries from the juice chamber to the condensers and then to atmosphere. Since the pressure in the last heating chamber is very low, a set of condensers is required to decrease the vapour pressure in the juice chamber too. In this way the temperature at which the juice starts boiled drops to a lower value and evaporation is possible.

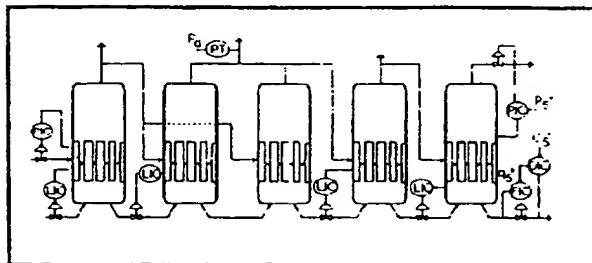


Fig. 3: Instrumentation and control structure

Fig. 3 shows the instrumentation and control strategy. The control strategy includes four level indicator controller, two preasure indicator

controller and a cascade concentration-flow control system. The instrumentation includes also measurement of the vacuum pans demand.

### 3. NONLINEAR MODELLING

The nonlinear mathematical model of the plant is obtained by applying simple physical laws. First we consider the modelling of a single evaporator. Later, we link all the models together.

Balances of mass, sugar and energy of the juice chamber of a evaporator lead to the following equations at time  $\tau$ :

$$dm/d\tau = q_i - q - q_e \quad (1)$$

$$d(mc)/d\tau = q_i c_i - q c \quad (2)$$

$$d(mh)/d\tau = q_i h_i + Q - q h - q_e H \quad (3)$$

where  $q_i$  and  $q$  are the input and output mass flows of juice respectively,  $c_i$  and  $c$  are juice sugar content of both flows and  $q_e$  is the steam flow obtained by boiling. The juice enthalpy  $h$  is a known function of  $c$  and temperature  $T$ . Steam enthalpy  $H$  depends on pressure  $p$  and temperature  $T$ .

As hypothesis we assume that the steam in the vapour space of the juice chamber is in equilibrium with the boiling juice. Then, the pressure in this chamber is determined by the equilibrium relation linking  $T$ ,  $c$  and  $p$ .

The heat from the steam to the juice is

$$Q = K (T_s - T) \quad (4)$$

where the heat transmission coefficient  $K$  is a function of the juice level in the tubes  $l$  and  $c$ .  $T_s$  is the saturation temperature.

The time constants associated with mass and energy balances in the heating chamber are neglectable compare to those in the juice. So, we can assume steady-state behavior, i.e.,

$$Q = F_s (H - h) \quad (5)$$

$$\log(P_s) = 2147 / (T_s + 273.2) + 5.76 \quad (6)$$

$F_s$  is the steam flow that enters the heating chamber.  $H-h$  is the latent heat of steam which is a function of the saturation temperature  $T_s$  ( $^{\circ}\text{C}$ ),

related to its pressure  $P_S$  (bars) by Antoine's law (6).

If we also assume steady-state in the vapour space of the juice chamber, then

$$q_e = K_v \sqrt{p^2 - p_o^2} \quad (7)$$

$K_v$  being an installation dependent coefficient and  $p_o$  the atmosphere pressure.

Finally,  $q_i$  and  $q$  are functions of valve openings as well as of pressure and level of juice (measured from the valve position):

$$q = K_j \sqrt{(p + d_j g l - p_o) d_j / (1/u_1^2 + K_{j1})} \quad (8)$$

$$q = K_{j2} \sqrt{(p_1 - d_j g l - p) d_j / (1/u_2^2 + K_{j3})} \quad (9)$$

$u_1$  and  $u_2$  are valve openings and the  $K_j$ 's are valve dependent coefficients;  $p_1$  is a contour pressure. The level  $l$  can be obtained from the total juice mass  $m$ , level juice  $l_o$ , mass juice  $m_o$  (at the bottom of the tubes) and the evaporators cross section surface  $S$  as

$$l = l_o + (m - m_o) / (S d_j) \quad (10)$$

The juice density  $d_j$  can be calculated from  $T$  and  $c$ .

The model of the whole evaporation station is obtained by repeating all the equations five times, and equating outputs flows and pressures of an evaporator with the corresponding input of the next one. A library of physical properties of steam and sugar juice is used to obtain the juice and steam enthalpies, densities, etc. Other data as valve coefficients, installation dependent coefficients and so on are taken from the technical documentation of the factory.

#### 4. PLANT ANALYSIS

##### 4.1 Control problems

In this process there are two main control aims to consider:

- Maintaining steady constant concentration of sugar at the output, specially to reduce large and repetitive disturbance effects.
- Keeping the juice level in each evaporator at

prescribed values for security.

We use  $PI$  control to regulate levels of fluid and pressures (see Fig. 3). A cascade  $PI$  controller regulates the juice sugar content and the juice flowrate. Note that variations in the juice flowrate change the resident time of the juice within the evaporator and consequently the concentration.

To maintain the level of juice, the control strategy varies the valves opening placed in the juice line at the input of each evaporator as it is shown in Fig. 2.  $PI$  control is sufficient to achieve this objective.

The most severe disturbance is the varying steam demand from the vacuum pan station which influences the operation of the system and the final output quality. The concentration is not more as constant as desired.

Fig. 4 shows a typical disturbance and its effect on the flowrate of juice at the input of the tank.

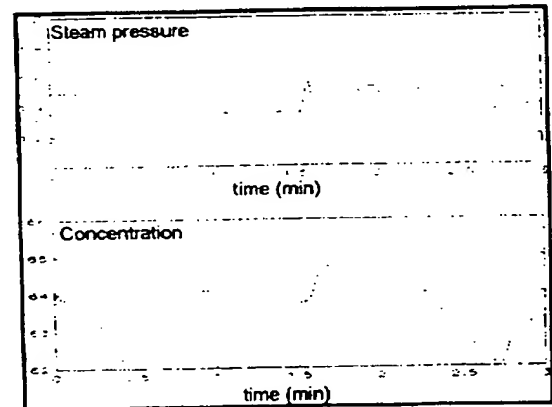


Fig. 4: Steam demand and output juice concentration

In order to design a concentration regulator providing good control performance we need a control system that results in a good disturbance rejection and robustness against the non-linearities present in the system. Fuzzy logic and GPC based regulators seem to be good choices for our purposes as we will see in the next sections.

##### 4.2 Open-loop responses

Fig. 5 shows open loop response of the juice concentration, when applying a negative step

in the flow set-point.

It could be seen, clearly, the existence of a delay in the process and the typical response of a non minimal phase system.

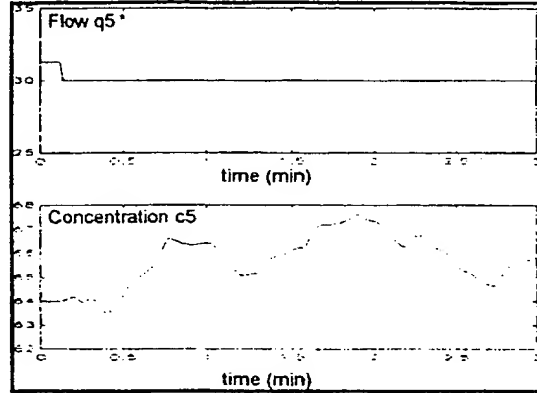


Fig. 5: Control signal and open loop response

#### 4.3 Linear modelling

By using the commercial software ACSL is possible to obtain from the nonlinear model, simplified linear models valid nearly specific operation points. We work out two function transfers in order to describe the relationship between output concentration  $c$ , flowrate-reference  $q_5^*$  and steam demand  $p_d$ . MATLAB was used to reduce the order and discretize the models with sampling time of 0.06 hour. The transfer functions are the following:

Output flowrate set point

$$\frac{c_5}{q_5^*} = \frac{q^{-1}(-0.127 + 0.13q^{-1} - 0.048q^{-2})}{1 - 1.8q^{-1} + 1.055q^{-2} - 0.184q^{-3}} \quad (11)$$

Steam demand

$$\frac{c_5}{p_d} = \frac{q^{-1}(3.74 + 3.93q^{-1} - 0.19q^{-2})}{1 - 1.8q^{-1} + 1.055q^{-2} - 0.184q^{-3}} \quad (12)$$

### 5. REGULATORS DESIGN

#### 5.1 Fuzzy logic control

Fuzzy logic provides an alternative solution to nonlinear control. A typical fuzzy expert controller comprises three elements: membership functions to fuzzify the physical inputs, an inference

engine with a decision rule base and a defuzzifier that converts fuzzy control decisions into physical nonfuzzy control signals. With these components, a complex nonlinear controller can be built.

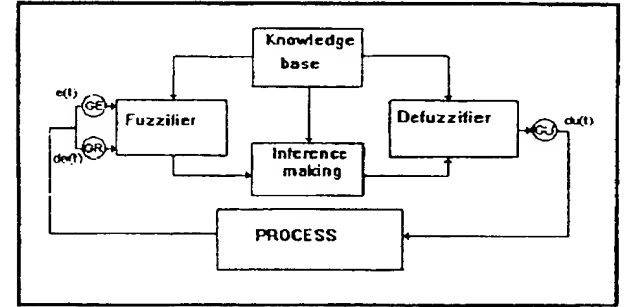


Fig. 6: Structure of the fuzzy logic regulator

Fig. 6 shows the block diagram of the fuzzy controller used in this study. The inputs to the fuzzy controller are error  $e(t)$  and

$$de(t) = e(t) - e(t-1), \quad (13)$$

the difference between the present and the previous error. The output  $du(t)$  is the incremental change of the control signal given by

$$u(t) = u(t-1) + du(t) \quad (14)$$

$GE$ ,  $GR$  and  $GU$  are parameters to be tuned.

Table I presents the incremental control rules, in form of a fuzzy control matrix. This fuzzy control matrix, proposed by Tang (1987), involved seven linguistic terms to characterize each variable: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium) and PB (positive big).

The control matrix is based on the following principles:

- If the output has the desired value and the error change is zero, then the output of the controller remains constant ( $du(t)=0$ ).
- If the output  $y(t)$  diverges, the action depends on the signum and the value of error  $e(t)$  and the error change  $de(t)$ . If the conditions are such that the error can be corrected quickly by itself, the controller output remains constant or almost constant. Otherwise, the controller output is changed to achieved satisfactory

results.

Table 1

	e(t)						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NM	NM	PS	ZE	PS	PM	PM
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

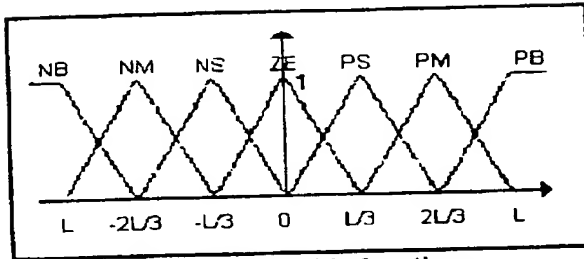


Fig. 7: Membership functions

As Fig. 7 shows, in this study we use triangular membership functions. A standard center of area method was used for defuzzification.

## 5.2 Generalized predictive control

A generalized predictive controller is based on a model of the system decibed by

$$A y(t) = q^{-1} B u(t) + C v(t) + D/\Delta w(t) \quad (15)$$

where  $y(t)$  is the output,  $u(t)$  the input,  $v(t)$  a low frequency disturbance,  $w(t)$  a white noise,  $A$ ,  $B$ ,  $C$  and  $D$  polynomials on the delay operator  $q^{-1}$ , and  $\Delta = 1 - q^{-1}$ .

The predicted output  $y_p(t+j)$  over a range up to the prediction horizon can be obtained as a function of the polynomials  $A$ ,  $B$ ,  $C$  and  $D$ , the past outputs  $[y(t), y(t-1), \dots]$ , future set points  $[r(t+1), r(t+2), \dots]$ , past controls  $[u(t-1), u(t-2), \dots]$  and a vector of potential future controls  $[u(t), u(t+1), \dots]$ .

The GPC algorithm calculates the vector of future controls by the minimization of the cost

function:

$$J_{GPC} = \sum_{n1}^{n2} e^2(t+j) + \sum_1^{nu} \alpha [u(t+j-1) - u(t+j-2)]^2 \quad (16)$$

where  $n1$  is the "costing horizon",  $n2$  is the "prediction horizon",  $nu$  is the "control horizon" after which the control increments are supposed to be zero,  $\alpha$  is a factor that weights the control efforts. The error  $e(t)$  is given by

$$e(t+j) = r(t+j) - y_p(t+j) \quad (17)$$

We can get feedforward actions to compensate for the disturbances  $v(t)$  by including the  $C$  polynomial in the model. The noise affecting the output of the system is also consider in the control design through the polynomial  $D$  of the model which can be modified to improve the control performance.

## 6. SIMULATION EXPERIMENTS

### 6.1 Basis for the evaluation

A set of simulation experiments with differents controllers are presented in this section. The output of the system is the concentration ( $c_5$ ) and the control signal is the flowrate setpoint ( $q_5^*$ ). The disturbances acting on the system are the steam demand from the vacuum pans ( $p_d$ ) and the pressure set point in the juice chamber of the fifth evaporator ( $p_5^*$ ) (see Fig. 2).

### 6.2 PI control

This experiment was carried out by using a continuous PI controller to maintain the concentration close to the reference signal. The controller was tuned by a trial and error procedure that gives following values for the proportional gain  $K_p$  and the integral time  $T_i$ :

$$K_p = -3 \quad T_i = 0.02 \text{ hour}$$

Fig. 8 shows the set-point  $c_5^*$ , the output  $c_5$  and the control signal  $q_5^*$ . As we can see the variance of the concentration is quite high mainly because of the disturbances acting on the system.

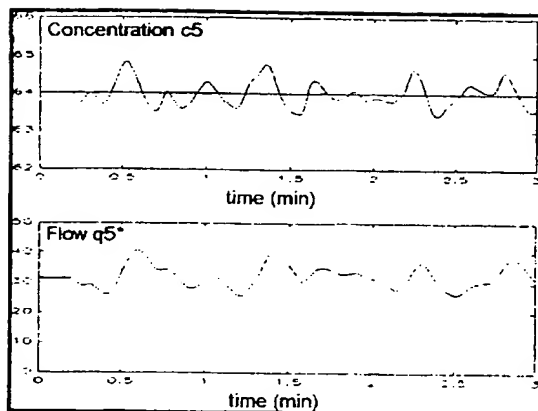


Fig. 8: Plant response and control signal with PI control

### 6.3 Fuzzy logic control

The regulator used in this experiment corresponds to the controller described in 5.1. The controller is characterized by the following parameters:

$$GE = -1 \quad GR = -0.05 \quad GU = 30$$

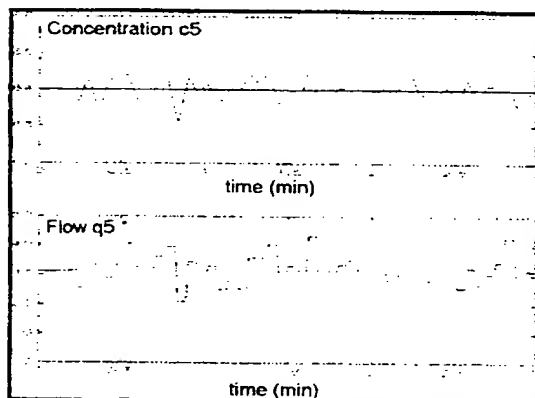


Fig. 9: Plant response and control signal with fuzzy control

Fig. 9 shows the set-point  $c_5^*$ , concentration  $c_5$  and the control signal  $q_5^*$  obtained with fuzzy control. We appreciate that concentration response improves considerable, compared with Fig. 8.

### 6.4 GPC control

We implemented first the control algorithm without considering the feedforward polynomial

( $C=0$ ). The design parameters in this case were:

$$n1 = 2 \quad n2 = 10 \quad nu = 2 \quad \alpha = 0.03$$

The results by considering constant reference are given in Fig. 10. The process behaviour with GPC control is also better than with PI control.

In order to reduce the variance of the output  $c_5$  we consider in the model the  $C$  polynomial corresponding to the steam demand. A feedforward component is therefore included in the control law. Fig. 11 shows that the output variance has been drastically reduced.

The influence of the weighting factor on the control efforts can be observed by comparing the last result with Fig. 12, obtained with  $\alpha=0.01$ . In this case the control efforts are greater and the output variance is smaller.

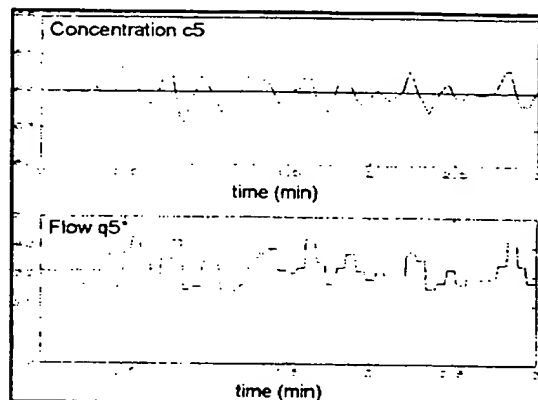


Fig. 10: GPC without feedforward action

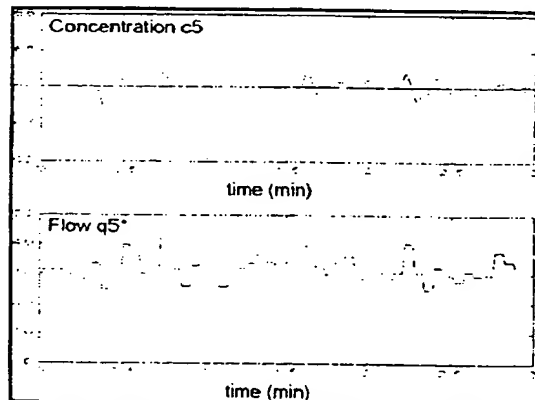


Fig. 11: GPC with feedforward action



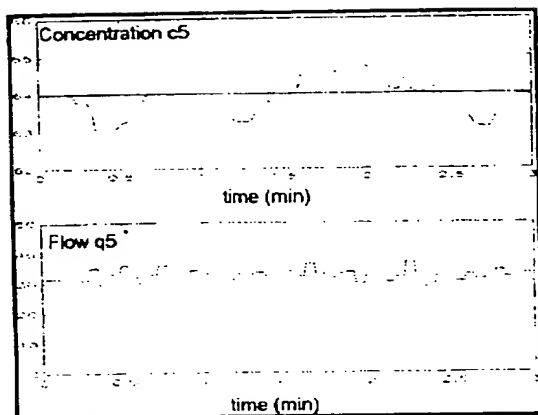


Fig. 12: Effect of the weight factor

### 6.5 Comparison

Table II presents a quantitative comparison of the performance of the three regulators, based on experimental results presented on Fig. 8, 9 and 11. Mean value and root mean square of two important variables, error  $e(t)$  and incremental change  $du(t)$ , are considered as comparison index.

Table II

Indexes of performance	PI Control	Fuzzy Control	GPC Control
mean-e	0.0015	0.0025	0.0045
rms-e	0.3179	0.2362	0.2628
mean-du	0.0009	0.0012	0.0066
rms-du	0.5144	2.7287	2.0438

### 7. CONCLUSION

The work carried out allowed to evaluate two advanced control techniques applied to a process of complex dynamic behavior as the evaporation station.

The results confirm the better performance of fuzzy and predictive controllers over PI control. The juice concentration shows much less variance, in spite of the disturbance that it affects.

The fuzzy controller doesn't require a mathematical model and the computational requirements are less in comparison with GPC controllers. These differences result quite attractive

for purposes of implantation in industrial plants.

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### 9. ACKNOWLEDGEMENTS

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